Model Based Performance Analysis (MBPA) of Nuclear Weapon Stockpile Electrical Systems

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Abstract

The primary mission of Sandia National Laboratories is to ensure that the U.S. nuclear arsenal is safe, secure, reliable, and can fully support our Nation's deterrence policy. With no new designs being produced and an ever aging stockpile, the mission presents increasing challenges. A ban on underground nuclear testing has necessitated a reliance on modelling and simulation of weapon systems. Model Based Performance Analysis (MBPA) provides a process for assessment of weapon electrical system performance through the use of SPICE-like simulations. A variability analysis technique has been developed that relies upon specification tolerances of components in the stockpile. This method creates a series (100s) of simulations, each one a unique description of the circuit. All component values are selected by Latin Hypercube Sampling (LHS) from their predefined tolerance range. High performance multi-processor computational platforms are used to attain fast simulation throughput. Key contributors to output parametric variation are determined by evaluating correlation coefficients calculated from observed variations in component values (independent variables) and the corresponding outputs (dependent variables). Identification of the key components creates a focus for stockpile testing and a predictive capability to surveillance activities.

1. Introduction

With the end of the Cold War long past and the subsequent U.S. policy of no new nuclear weapon designs, the "enduring stockpile" is ever increasing in age. Assessing the safety, security, and reliability of the systems in the inventory has taken on added importance due to the affects of aging mechanisms in materials and their potential impact. In addition, the moratorium on underground nuclear testing has increased the importance of, and reliance upon, modelling and simulation to provide confidence in the performance of systems. Modelling and simulation of weapon systems is now a major focus of the national laboratories tasked with stockpile stewardship. Model Based Performance Analysis (MBPA) uses modelling and simulation of weapon electrical systems to better understand baseline system variability and how the aging of materials in electrical devices affects system performance and lifetime. Additionally, with the incorporation of device tolerances it allows a thorough investigation of the performance space which leads to a more complete understanding of worst case environments and a better characterization of margins to failure. Current surveillance of the stockpile is very reactionary in that performance issues associated with aging are addressed as a consequence of unsatisfactory surveillance testing results. By providing a technique to bridge between material aging effects in electrical devices and system performance, MBPA provides a predictive capability to the monitoring of the stockpile. A principle product is a circuit sensitivity analysis that identifies the electrical devices that are key contributors to system performance variability. This information is used to focus future surveillance testing in areas where aging trends are most likely to cause performance deterioration.

2. Sensitivity Analysis

2.1 Circuit Model Development

Once a system has been selected for study, an electrical circuit model is developed. Typically, a schematic of the circuit is constructed using one of many commercially available schematic entry systems. The circuit schematic visually describes all input stimuli in the circuit, passive components, semiconductor devices, and their connectivity. Associated temperature dependent SPICE-compatible models for each of the semiconductor devices in the circuit are contained in a separate text file that is linked to the circuit schematic. Semiconductor device models consist of a large number of parameters specific to the device that describe the physics of its operation. Tests of interest are identified from system specifications and the appropriate input stimuli are incorporated into the circuit. With a complete description of the circuit, a baseline simulation of performance can be run. Simulations are conducted using any one of several SPICE-like simulation codes on single or multi processor computational platforms. Simulation run times can vary from fractions of a second to many days, depending upon circuit complexity and computational processing power. A comparison of the results to product specifications helps to verify circuit model functionality and acts as a check to verify reasonable performance. To gain further insight, baseline simulation performance is compared to test data for the circuit under study. For verification of circuit model fit, the simulated performance of the output parameter of interest should fall within the distribution of test data.

2.2 Sensitivity Input and Propagation

With the development of a validated circuit model complete, a sensitivity analysis of the circuit can be defined and executed (Figure 1). The goal is to determine the circuit components that are the key contributors to output parametric variation. This is accomplished by running a large number of simulations of the circuit incorporating component variation and observing the resulting impact upon output performance. The first step is to identify the output performance metrics of interest for the circuit, typically these come from product specification documents. The output metrics chosen will be the dependent variables in the analysis. Next, components to be studied in the circuit are identified and component variations are the independent variables. Tolerances and temperature dependencies for each of the passive components in the study are compiled and device models representing the minimum and maximum specified performance for each of the semiconductor devices are developed. By incorporating the tolerances, temperature dependencies, and minimum/maximum models into the sensitivity analysis, the entire performance space can be thoroughly investigated.

Latin Hypercube Sampling (LHS) (McKay, Conover, and Beckman 1979) is used to select values for the passive components in the circuit and one of three model references (minimum, nominal, maximum) is selected for each of the semiconductor devices. The number of observations, n, is chosen based upon the number of circuit components in the study. A file is generated listing all circuit components (independent variables), k, in the analysis, the range of possible values for each and the type of distribution. The file is input to a LHS computer program (Iman, and Shortencarier 1984) that calculates the observations for each of the components. A LHS vector file is created with an $n \times k$ matrix of input for the simulation where the ith row comprises selected values for each of the k independent variables to be used in the ith run of the simulation.
The LHS vector file is combined with a netlist template to produce n netlists for simulation. A netlist is a line by line description of the circuit that includes connectivity of the components, component values, semiconductor device models, input stimuli, definition of the output data required and simulator controls.

2.3 Circuit Simulation

The n netlists are simulated on multi-node (100-1000s) UNIX or Linux computational platforms with SPICE-like simulation codes, such as Xyce™, a code developed at Sandia National Laboratories and optimized for use on large-scale parallel computing platforms. The result is n output files containing the output performance metrics of interest. Simulations can be repeated for any other temperatures of interest. By leveraging efficient simulation codes and very powerful computational platforms the actual simulation time can be decreased by orders of magnitude.

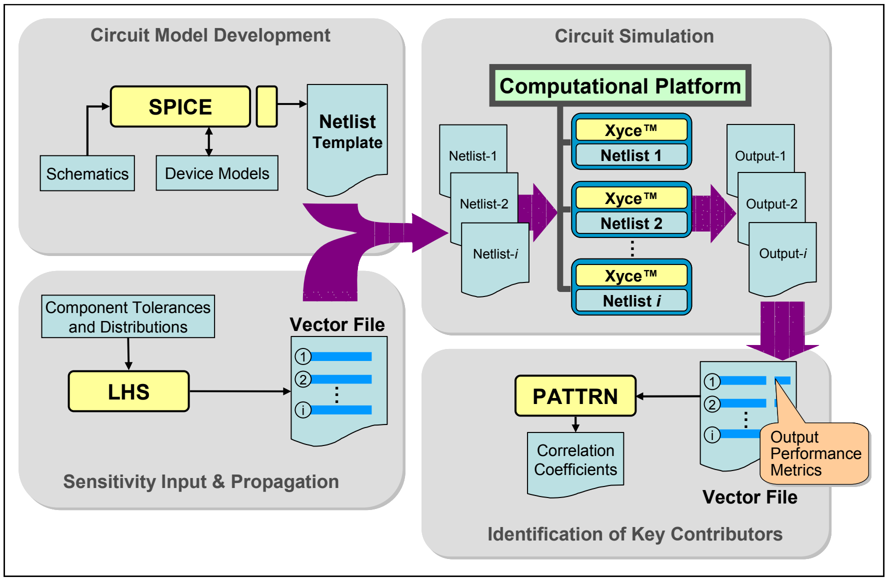

Figure 1: Sensitivity Analysis

2.4 Identification of Key Contributors

The output files are combined with the LHS vector file to generate a file pairing the *i*th set of component observations (independent variables) with the *i*th set of output parameters (dependent variables) to create another vector file. The output vector file is input into PATTRN, a program developed by Shortencarier, and Helton (1999), to calculate Pearson correlation coefficients and partial correlation coefficients. Scatterplots of each output parameter versus each circuit component are also generated. Review of the correlation coefficients and scatterplots (Figure 2) identifies the components that are the key contributors to output parametric variation. The identification of these components can be used to focus future surveillance testing and provide subjects for accelerated aging studies. Monitoring of the key components will help in the early detection of any aging trends that could potentially impact system performance.

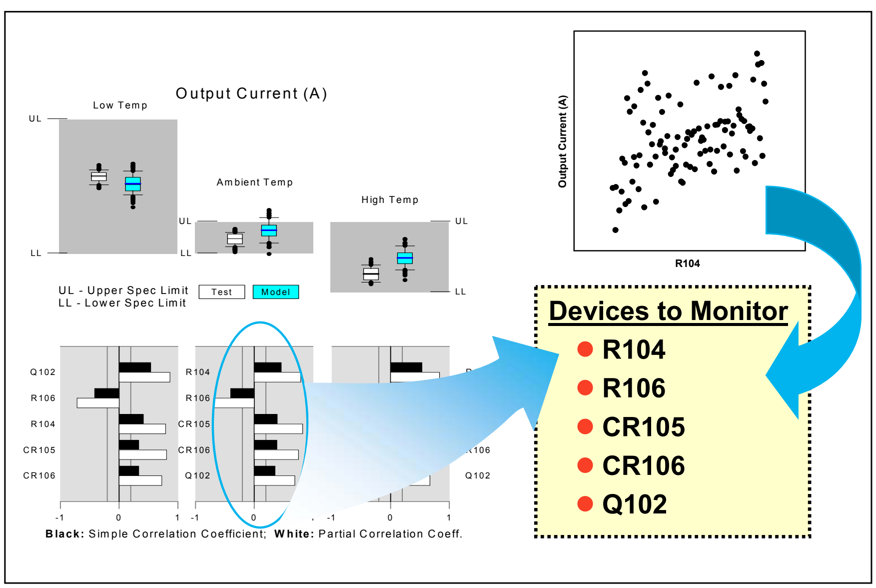

Figure 2: Example of Identification of Key Contributors

3. Model Validation and Aging Trends

Surveillance monitoring and testing of key contributors in a system can provide vital data for circuit model validation. The most meaningful testing includes not only system output waveform and limit to specification data, but tests of internal components and component model development. The component models extracted can be integrated into the system electrical circuit model to simulate the performance of that particular unit. Simulation waveforms and data are directly compared to measured waveforms and data for the unit. This effort provides a very good validation of the electrical circuit model. With a validated circuit model, data from aging studies conducted on key contributors can be added. Subsequent simulations can indicate system performance trends as a result of component aging and help to quantify any changes in performance margins. Based upon any observed aging trends predictions of system lifetime can be made.

4. Conclusion

Increasing age in the stockpile and a ban on all underground nuclear testing has necessitated an increased reliance upon the modelling and simulation of weapon electrical systems to assess performance. MBPA makes use of modelling, simulation, and a sensitivity analysis technique to identify the components within a weapon electrical system that are the key contributors to output performance variation. An increased focus of surveillance efforts upon these components will provide an increased understanding of how trends in aging effects may potentially impact electrical system performance. This predictive capability is a much needed tool in the stewardship of the stockpile.

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